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XXII.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

XLIII.—EXPERIMENTS ON THE RELATION OF
HYSTERESIS TO TEMPERATURE.

BY FRANK A. LAWS AND HENRY E. WARREN.

Presented by Charles R. Cross, October 10, 1894.

THIS paper gives an account of some experiments to determine the effect of temperatures much above the normal on the dissipation of energy by hysteresis in a specimen of steel.

At the time of the beginning of this research, in February, 1894, there were no complete studies of this subject known to us. A casual reference is to be found in the Proceedings of the American Institute of Electrical Engineers, Vol. VII. p. 325, 1890, by Prof. Harris J. Ryan. The tests there referred to were made on a cast-iron ring. The maximum temperature employed was 360° . The details of the measurements are not given. A short paper by Dr. Wilhelm Kuntz appeared in the *Electrotechnische Zeitschrift*, Vol. XIII., May 6, 1892. In this Dr. Kuntz showed that the hysteresis loss decreased with rise of temperature. A second paper by the same author appeared in the *Electrotechnische Zeitschrift*, Vol. XV., April 5, 1894. The magnetometer method was used by Dr. Kuntz in this work. In this paper tests of several ferrous materials are given, as well as some on a specimen of nickel.

At the outset of this research it was decided that alternating currents should be used, and that the losses should be determined by a Wattmeter, thus reducing the time required for observations to a minimum. The instrument which we designed and used is shown in Figure 1. We have decided to call the arrangement a Watt-balance. Mr. A. E. Kennelly has given in the *Electrical Engineer*, December 21,

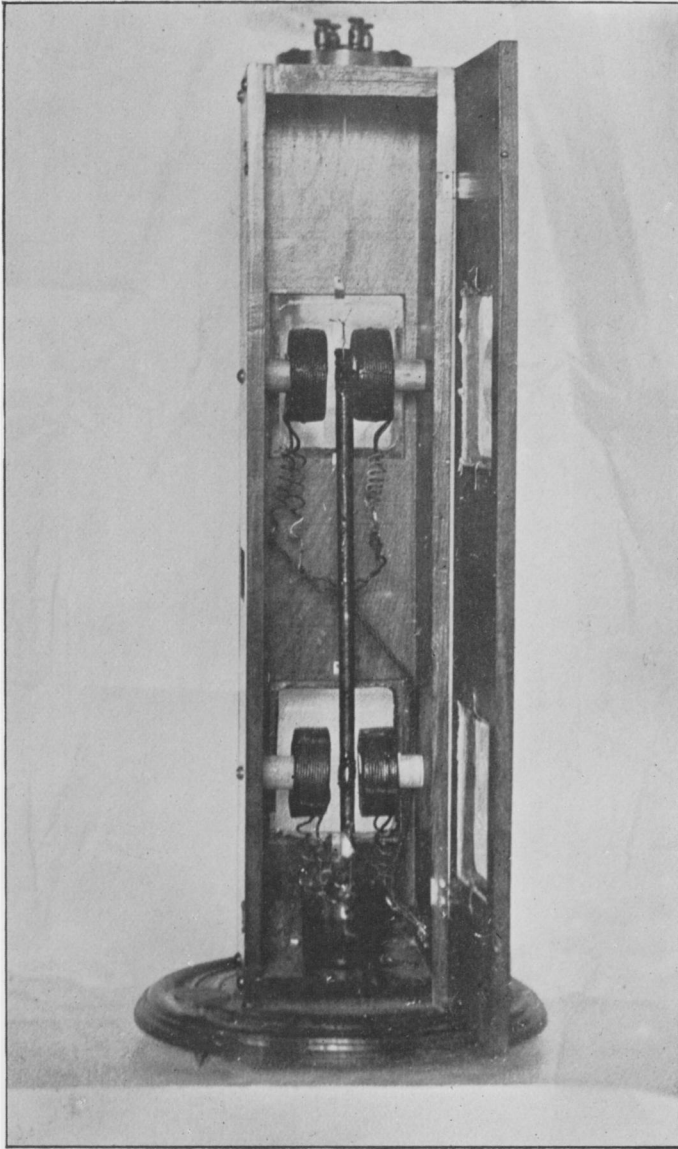


FIGURE 1.

1892, a description of a "Differential Wattmeter." This instrument gives the difference of the mean values of two definite integrals representing the primary and secondary energy in a transformer; that is, the losses. The Watt-balance measures the ratio of the mean values of two definite integrals. It can therefore be used to measure the efficiency of a convertor, giving the result by a single reading.

The Watt-balance consists of two electro-dynamometer Wattmeters, one above the other. The movable coils are rigidly connected in our instrument by a spiral-wound paper tube, and consist of 100 turns of silk-covered German silver wire No. 32 B. & S. gage. The resistance, including leads, is 103 ohms; the diameter of coils, 2 cm. In series with the movable coils are two adjustable resistances, r_1 and r_2 , as shown in Figure 2. The stationary coils are arranged in pairs; each is 2.3 cm. in mean radius, and contains 130 turns of No. 12 cotton-covered wire. They are movable along their axes, so that the factor of the instrument may be adjusted. The vertical distance between the two dynamometers is 30 cm. The movable parts are suspended by a silk thread inside a narrow paper tube to prevent disturbance by air currents, and directive force is given by four spiral springs, made of copper wire 0.005 cm. in diameter. These springs serve as leading in wires for the movable coils. The instrument is read by a telescope and scale.

In Figure 2 is shown the scheme of connections for a hysteresis test. At the left the slide resistances for controlling the currents are shown. By the proper insertion of the connection, C , either a direct or an alternating current could be sent through the remainder of the apparatus, which in the main circuit consisted of an electro-dynamometer, one pair of stationary coils, the specimen under test, a known resistance, R , of German silver strip immersed in kerosene oil to keep it at a constant temperature, and the second pair of fixed coils. At one terminal of R a connection was made by means of a short piece of stout wire and a key, K ; beyond the key the circuit branched, passing through the adjustable resistances r_1 and r_2 , the proper movable coils, and returning one lead to the external terminal of the specimen, and the other to the corresponding terminal of R . The resistance r_1 was some hundreds of ohms, seldom falling below 300, and was more frequently in the neighborhood of 1,000; r_2 was kept at a constant value, 976 ohms. The resistances r_1 and r_2 were ordinary plug boxes, and the assumption was made throughout the work that the resistances of circuits r_1 and r_2 were so high in comparison with their inductances that no correction factor need be applied to the indications of the

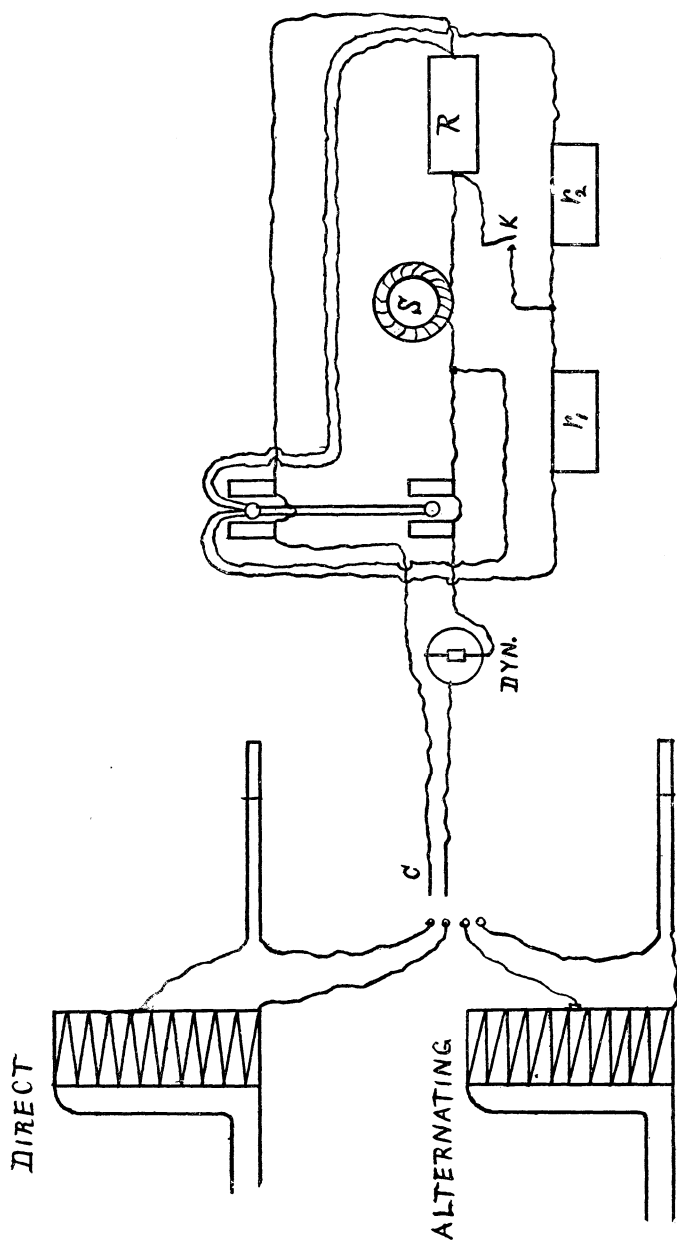


FIG. 2.

Watt-balance. It may be well to mention that the use of high resistances constructed in the usual way by double winding may lead to serious errors in alternating current measurements on account of the capacity effects.

If the plug C be inserted so that a current flows in the apparatus, and no deflection is observed, then the factors of the upper and lower dynamometers are equal; if the key K is depressed, there will in general be a deflection, which may be reduced to zero by adjusting r_1 , as a zero reading means that the average values of the products of the currents in the two coils of the upper and lower dynamometers are the same. It is known that the work in S bears the same ratio to the work in R that the total resistance in circuit r_1 does to the total resistance in circuit r_2 . If the current is alternating, the work in S is of course divided between hysteresis and heating losses. No allowance has been thought necessary for the work done in the suspended coils. If W_s and W_R represent the work in the specimen and in R , then

$$W_s = W_R \left(\frac{r_1 + 103}{r_2 + 103} \right) = \frac{I^2 R (r_1 + 103)}{r_2 + 103},$$

I^2 is given by the electrodynamicometer *DYN*.

To correct for the heating loss in S a direct current of any convenient magnitude is sent through the circuit, and a second balance, r_1^1 , obtained,

$$R = 1,079 \text{ ohms, } r_2 = 976 \text{ ohms; so } W_s = \frac{I^2}{1000} (r_1 - r_1^1).$$

It will be seen that the Watt-balance as used in the present case is a Wattmeter with an electrodynamic control. The advantage derived from obtaining this control by shunting a portion of the main current is that any manipulation of the circuits does not disturb the equilibrium of the instrument, and that it renders it possible to use the instrument in a null instead of a compensation method.

As the hysteresis loss is a function of the maximum magnetization, denoted by B , it was necessary to provide some means by which the maximum might be kept constant, and its value determined. The device sketched in Figure 3 was used for this purpose. In addition to the magnetizing coil, the specimen was provided with a winding of 24 turns, which was connected in series with an adjustable resistance of 874 ohms during the tests, and a galvanometer of 126 ohms. Leads were carried to the dynamo room, and terminated in brushes which rested on the edge of an ebonite disk 11 inches in diameter, fastened rigidly to the dynamo shaft; the brushes were carried by a radial arm,

the motion of which is controlled by a small magneto-motor driven by three Leclanche cells. The motor was governed by a reversing key in the testing room, about one hundred feet away. The alternator used had ten poles, thus making the length of a wave 72° . A piece of brass, 36° or one half a wave long, was set into the edge of the disk, and the whole carefully trued up. When the dynamo was in action the B current was closed once during a revolution, and for a time corresponding to one half a wave length. The galvanometer then performs the operation

$$\frac{2}{T} \int_{t^1}^{t^1 + \frac{\pi}{2}} C dt$$

fifteen hundred times a minute. The value of this integral will be a maximum when it extends over the time between $+B$ and $-B$. By

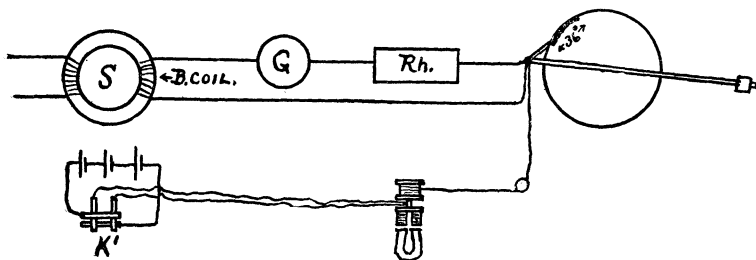


FIG. 3.

the use of the key K^1 the brushes may be shifted, and the reading of the galvanometer brought to its greatest value. With the dynamo running at its normal speed a Leclanche cell, E.M.F. 1.4 volts was inserted in the circuit; Rh was 1,374 ohms, and the deflection 21.2 cm.; with brushes short circuited and Rh equal to 14,874 ohms the deflection was 21.8 cm., the ratio of deflection being .972. If the brushes made perfect contact, and there was no self-induction effect, the ratio would be unity, the entire cycle of operation being performed in a time short compared with the period of the galvanometer. During the tests the reading with $Rh = 1,374$ was frequently repeated in order that the brushes might be kept in as uniform a condition as possible.

Owing to the manner in which the specimen is constructed, the area included in the B winding is but partially occupied by the iron. In calculating the approximate values of B no allowance has been made for this, as the permeability is high in the cases where B has been determined. If observations were taken at temperatures where the permea-

bility was very low, it would be necessary to apply a correction for this unoccupied area. The values of B were calculated by the formula

$$B = \frac{E^1 R D}{20 A N n R^1 D^1}.$$

D is the deflection corresponding to the value of B to be found. R is the resistance in circuit $R h$; N , the number of turns on B winding. n , the number of revolutions per second. A is the area of the iron included in the B windings. D^1 is the deflection of the galvanometer when an E.M.F. of magnitude E^1 and a resistance R^1 are inserted in the circuit $R h$, the dynamo turning at the normal rate.

The furnace used for heating the specimen was built of fire brick, the external diameter was about 36 inches, height 18 inches. Inside the fire brick was a layer of asbestos wool $2\frac{1}{2}$ inches thick, kept in place by asbestos board, which was protected by thin sheet iron. The box containing the specimen was made of asbestos board about $1\frac{1}{2}$ inches in thickness, and lined with retort cement. During the tests it was tightly closed. The furnace was heated by three blast jets made of gas pipe, the external tubes were $\frac{3}{4}$ inch inside diameter, the inner tube $\frac{3}{8}$ inch. The supplies of gas and air were regulated by slide valves. The jets were directed into the furnace tangentially and with a slight upward inclination, the effect being to establish a good circulation and keep the interior of the furnace at a uniform temperature.

The specimen upon which the following tests were made was composed of so called French steel, which showed on analysis the following impurities: —

Manganese	0.535 per cent.
Phosphorus	0.013 “
Silicon	0.085 “
Sulphur	0.018 “
Carbon	0.970 “

The mass of iron employed was 628 grams. From this material, which was four one-thousandths of an inch thick, rings of 3 inches' outside and 2 inches' inside diameter were stamped, and the specimen formed by piling them. Each was insulated from its neighbors by a layer of pipe clay, applied as a sort of paint, the clay having been moistened with alcohol. Every tenth layer was insulated with mica. The pile so formed was wrapped with asbestos cloth, and the magnetizing coil of 36 turns of No. 14 copper wire wound on. The wire was insulated by winding it with asbestos twine. Interwound with

the magnetizing coil was the B coil of 24 turns. These two windings formed on the outside of the specimen a single layer. The temperatures were determined by a Le Chatelier pyrometer, calibrated by known melting points. The hot junction was placed inside the asbestos wrapping resting against the iron, the leads were brought out through the usual double-cored fire clay tube; this was surrounded by a piece of gas pipe thoroughly wrapped in asbestos cloth, because in using this pyrometer in a case like the present, where the leads pass from the hot junction through a space at a higher temperature at a short distance from the junction, it is necessary to guard against conduction along the leads, and consequent errors in the temperature.

The manner of making the tests and the subsequent calculation was as follows. Owing to the construction of the furnace, the specimen being well shielded from the heat of the flames by the internal chamber, the air insulation, and its own asbestos covering, the temperature of the iron rises gradually; consequently the specimen will be at very nearly a uniform temperature. When a reading is desired, the alternating current is turned on and the B deflection adjusted to its maximum value by K^1 , and to its correct numerical value by varying the magnetizing current. Watt-balance resistance r_1 is now adjusted, and the pyrometer reading corrected for zero, and dynamometer reading and time observed; after a few minutes the observations are repeated, the temperature having risen in the mean time. This process is kept up until the iron loses its magnetism. Occasionally, a direct current was sent through the apparatus and the Watt-balance, dynamometer, and pyrometer readings taken; these allow the value of r_1^1 in the hysteresis formula to be determined by making a plot, the co-ordinates being Watt-balance and pyrometer readings, from the plot the value of r_1^1 , corresponding to any pyrometer reading may be read off. The electrodynometers were calibrated by sending a direct current through them, and measuring the P.D. at the terminals of a known resistance by projection against the E.M.F. of a Clark cell; the values of deflections and currents squared were plotted, giving straight lines.[†] I^2 was determined by reference to these plots. The zero errors of the dynamometers employed were very variable, and were determined after each reading.

The results of the measurements will now be given. They are plotted as referred to at the beginnings of the several tables.

TABLE I.

FIRST HEATING : ASCENDING CURVE.

See Figure 4.

 $B = 1970$. $n = 125$. W_H = Hysteresis loss in specimen.

W_H .	Temp. °	W_H .	Temp. °
.852	23	.678	387
.834	45	.526	440
.845	67	.456	481
.845	98	.331	546
.817	132	.241	595
.809	181	.130	672
.818	272	.088	709
.742	347		

The specimen lost its magnetic properties so rapidly that further measurements could not be taken on the ascending curve.

TABLE I. — DESCENDING.

W_H .	Temp. °
.0	787
.161	576
.206	503
.255	445
.290	417

Power shut off.

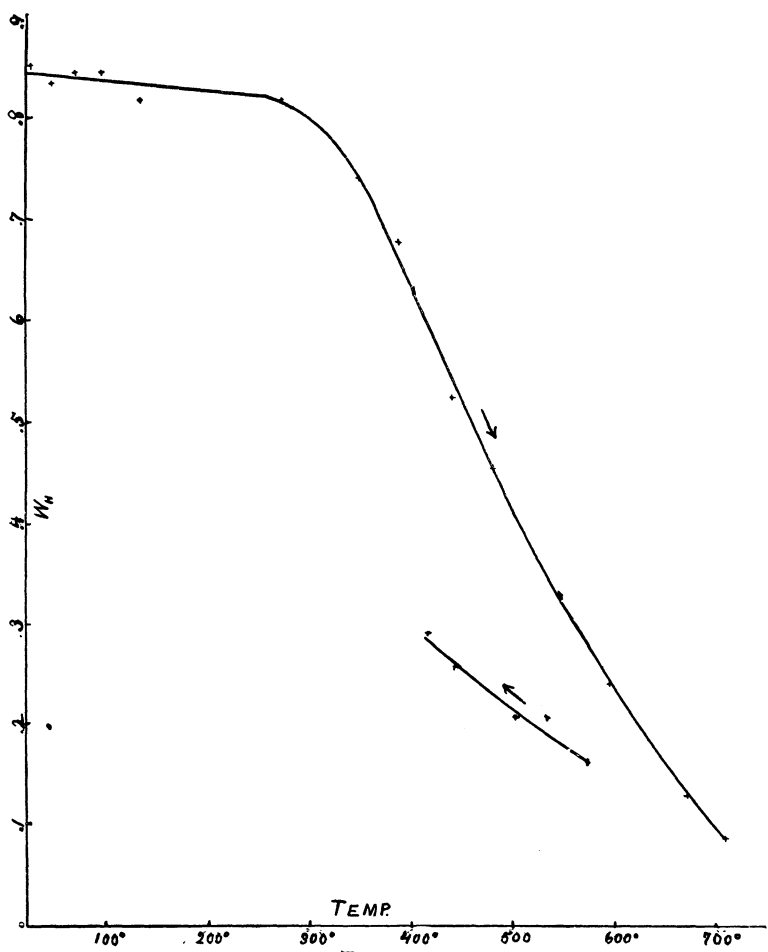


FIG. 4.

TABLE II.
SECOND HEATING : ASCENDING.

See Figure 5.

$B = 1974, n = 125.$

W_H	Temp.	W_H	Temp.
.516	20	.149	632
.520	75	.121	653
.519	108	.115	662
.522	160	.093	679
.440	269	.083	688
.407	310	.094	692
.378	345	.104	693
.340	397	.130	693
.321	423	.130	693
.311	438	.142	693
.293	470	.144	693
.258	511	.142	692
.228	555	.140	694
.167	593		

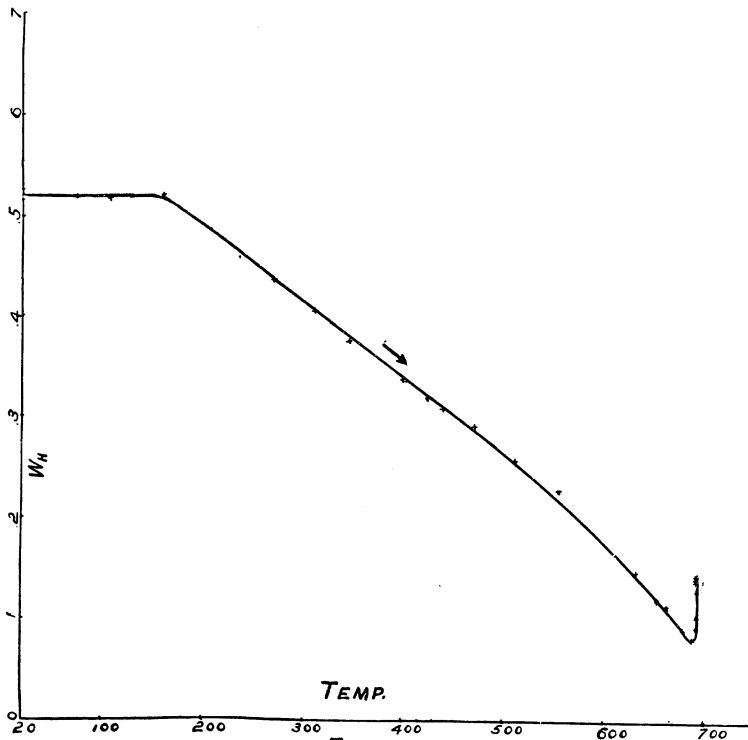


FIG. 5.

Inspection of the plots shows (Figs. 4 and 5) that for this sample of steel a moderate elevation of temperature up to about 270° has but a small influence on the hysteresis loss; that at this point a change takes place, and the diminution of hysteresis, with rise of temperature, is much more rapid, the decrease being such that at 675° the loss is but 13 per cent of its value at ordinary temperatures. After heating above the inflection point, the specimen shows on cooling a marked decrease of the hysteresis loss from its value at the same temperature on the ascending curve. If the specimen be heated again, a change of direction of the curve takes place, but at a lower temperature. The second plot (Fig. 5) shows an increase of the hysteresis loss after the point of inflection has been reached. As only two heatings were made, we were unable to verify these observations, the results of which became apparent only when they were reduced. In addition to the experiment at high temperatures, the following observations were made. A specimen was made up and the loss measured at the ordinary temperatures; a mean of three measurements gave .289 Watts as W_H . The specimen was then covered with a mixture of solid carbonic acid and ether; a mean of three measurements showed W_H as .288 Watts, showing that there is practically no change of hysteresis for a diminution of temperature to about -80° .

Between the ascending and descending observations of the second heating, readings were taken for the purpose of finding whether the temperature at which the iron becomes markedly magnetic on cooling is the same as that at which the sudden diminution of the magnetic properties occurs on heating. Simultaneous readings of the B galvanometer and pyrometer were taken, the current remaining constant, no adjustment for maximum was made. The readings, together with some from the descending curve of the first heating, are given below, and, after being corrected for zero, are plotted in Figure 6.

TABLE III.

First Heating.		Second Heating.	
B Reading.	Pyr.	B Reading.	Pyr.
38.8	7.17	28.1	6.99
38.8	7.10	29.9	7.01
38.8	7.05	31.0	7.02
38.8	7.00	32.1	7.03
38.7	6.95	33.4	7.05
38.55	6.90	34.8	7.10
38.15	6.83	36.1	7.11
37.70	6.80	37.2	7.12
37.00	6.73	37.9	7.13

First Heating.		Second Heating.	
<i>B</i> Reading.	Pyr.	<i>B</i> Reading.	Pyr.
36.3	6.69	38.3	7.14
33.65	6.51	38.6	7.15
31.2	6.45	38.7	7.15
		38.6	7.19
		38.8	7.14
		38.75	7.10
		38.75	7.03
		38.7	7.01
		38.65	6.98
		38.55	6.95
		38.25	6.93
		37.85	6.90
		37.1	6.85
		36.5	6.84
		34.1	6.76
		32.7	6.73
		30.7	6.70

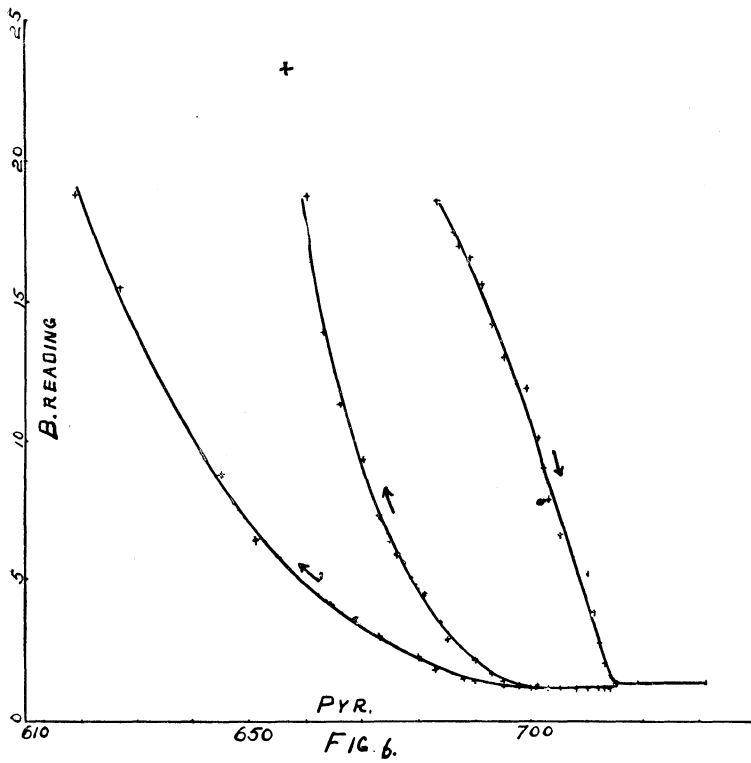


Figure 6 shows that the two points do not coincide, that on the descending being about 12° lower than that on the ascending curve. The difference of form of the curves is noticeable, showing that the regaining of magnetic properties on cooling is more gradual than their loss on heating; the sudden exaltation of magnetic properties occurs at the same temperature in the first and second coolings.

At the time of this writing the research has not been fully completed. We are, however, now engaged on further experiments, and hope to present additional data in the near future.

ROGERS LABORATORY OF PHYSICS,
June, 1894.